METHOD AND APPARATUS FOR FILTERING DIGITAL TELEVISION SIGNALS

BACKGROUND OF THE INVENTION

This invention relates to digital television and, more particularly, to methods and apparatus for filtering digital television signals to remove multipath and other undesirable effects upon a digital television signal as the signal propagates through a channel.

Digital television is an emerging technology that is the subject of much research both in the United States and Japan. Because of the potential advantages of digital television and the many technical problems associated therewith, research into improved systems and methods for transmitting and receiving digital television signals is increasing.

One of the most important prevalent problems associated with digital television signals is the problem of multipath effects. The term multipath, as used herein, refers to the propagation of electromagnetic waves along various paths from the digital television transmitter to the digital television receiver. Multipath effects may arise from fixed structures, such as building walls, acting as reflectors in the transmission channel. Moving objects, such as airplanes, may also cause a multipath condition. Even microreflections in cabling can cause multipath conditions. These structures can cause transmission of the television signal to occur along more than one path from the transmitter to the receiver. As a result, the same signal may be received more than once, and at different times by a single, or multiple, receivers. The result of multipath effects in analog television is to create "ghosts" in the displayed television image. In digital television, the effects of multipath can include moderate to severe degradation in the displayed TV picture and sound.

Various methods and systems have been designed to address the problem of multipath. See, for example, P. T. Marhiopoulos and M. Sablatash, "Design of a Ghost Canceling

Reference Signal for Television Systems in North America," *Proceedings of Canadian Conference on Electrical and Computer Engineering,* Vancouver, BC, Canada, Sep. 14–17, 1993, pp. 660–663.

The statistics of multipath ghosts have been studied and compiled by, among others, the BTA (Japan's Broadcasting Technology Association). The BTA, and other concerns, designed a "ghost canceling reference" (GCR) transmitted signal to mitigate these multipath effects. The BTA GCR was found to be less than satisfactory in some cases. While homes with outdoor antennas displayed non-varying (stationary) ghosting conditions which could be largely corrected, those homes with indoor antennas experienced changing (dynamic) ghosts. These ghosting conditions were more prevalent where people were moving about the room or other moving objects were in the signal path. The BTA ghost canceller generally was not able to adequately compensate for these conditions. Therefore, a need remains for a system and method for filtering out, or removing, multipath components from digital television signals, and especially for systems and methods for filtering multipath components from a digital television signal when the multipath component arises from moving objects and dynamic conditions in a transmission channel.

BRIEF SUMMARY OF THE INVENTION

In an exemplary embodiment of the invention a system for filtering digital television signals comprises a generator

for providing a first data sequence to a private data packetizer, and a transmitter for transmitting the packetized first data sequence in a data channel of a digital television signal. The system further includes a receiver for receiving the digital television signal and recovering the first data sequence. The receiver includes a channel estimator for providing an estimate of channel characteristics such as estimated channel impulse response and estimated noise variance. The receiver further includes an adaptive equalizer filter having an input for receiving the digital television signal and an input for receiving adaptive filter coefficients. The receiver further includes a coefficient processor for calculating adaptive filter coefficients and providing the adaptive filter coefficients to the adaptive equalizer filter. The equalizer filter is in communication with the output of the comparing circuit such that filter coefficients of the adaptive filter are adjusted according to the estimate of the impulse response of the data channel. In one embodiment of the present invention, the television transmission is coded according to a Motion Picture Experts Group (MPEG-2) standard.

A method of filtering a digital television transmission comprises the steps of generating a first data sequence at a transmitter and periodically inserting the first data sequence into a digital television bit stream to be transmitted. The method further comprises the steps of transmitting the digital television bit stream through a channel to a receiver, receiving the digital television bit stream and extracting the first data sequence from the digital television bit stream. The extracted first data sequence includes channel induced noise. The method further includes the steps of comparing the extracted first data sequence, including channel induced noise, to a second data sequence. The second data sequence is locally generated, that is, the second data sequence is generated at the receiver and does not include channel induced noise. However, in one embodiment of the present invention the second data sequence contains the same data as the first data sequence. The method further includes a step of provide a channel estimate based on the comparison step. The method further includes the steps of applying the received television bit stream to an adaptive filter and adaptively adjusting filter coefficients of the adaptive filter according to the channel estimate such that undesirable channel effects, such as noise, upon said received television bit stream are filtered from said received television bit stream.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects and advantages will be better understood from the following detailed description of a preferred embodiment of the invention with reference to the drawings, in which:

FIG. 1 is a block diagram of a digital television transmitter according to an embodiment of the present invention;

FIG. 1A is a block diagram of a digital television receiver including a filter according to the present invention;

FIG. 2 is a block diagram of an embodiment of a channel estimator according to the invention;

FIG. 3 is a block diagram of one embodiment of an equalizer filter according to the present invention;

FIG. 4 is a flow diagram of a method for generating equalizer coefficients according to one embodiment of the present invention;

FIG. 5 is a block diagram of a decrypter according to one embodiment of the present invention; and

FIG. 6 is a timing diagram showing a rolling frame training sequence according to the fourth aspect of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Transmitter

FIG. 1 is a block diagram of one embodiment of a digital television transmitter 10 adapted according to the present invention. Digital television transmitter 10 includes circuitry typically used and generally known in the art of digital television to packetize and encode audio and video signals for transmission to a digital television receiver. Typical circuits include video encoder/packetizer 12, audio encoder/packetizer 14 and private data encoder/packetizer 16. Private data encoder/packetizer 16 is used to encode and packetize what is known in the art as a private data stream. Typical uses for a private data stream include carrying parity bits for other data packets, allowing for increased error detection and correction. The private data stream may also be used to carry measured distortion. Measured distortion is distortion purposely introduced as part of a pay for quality service.

The present invention relies upon use of the private data stream of a packetized digital television signal. According to the present invention, transmitter 10 includes a data sequence generator 20. Data sequence generator 20 generates a predetermined sequence of digital bits. Any sequence of bits can be selected for generation by first data sequence generator 20. The particular sequence selected is not important as long as the sequence is a known and repeatable bit pattern suitable for packetization. The data sequence from first data sequence generator 20 is provided to private encoder/packetizer 16 where it is encoded and packetized in the same manner as other private data such as parity bits.

The packetized data sequence is then combined by mulitplexer 22 with packetized audio and video signals in accordance with a digital formatting standard to provide digital television stream 25. In one embodiment of the present invention the MPEG-2 (Motion Picture Expert Group) coding standard is employed. In alternative embodiments of the present invention the digital television signal is coded generally in accordance with the ATSC (Advanced Television Standards Committee) standard. The ATSC standard, which includes the MPEG format, allows each 19.3 Mbps of information to be time divided into video, audio, and private data channels. The information is transmitted in packets of 188 bytes, and each packet begins with a packet identifier (indicating which data stream it belongs to, for example, voice stream number three or video stream number one, etc.). Accordingly the packet containing the data sequence generated by first data sequence generator 20 is identified as belonging to a "private" data stream. Digital television stream 25 is transmitted, or broadcast, as a digital television signal through channel 600 to a digital television receiver. It will be recognized by those skilled in the art that the invention is not limited to MPEG signal formats. In fact, the invention could be utilized with any digital television signal carrying information in packets.

Receiver

FIG. 1A is a block diagram of a digital television receiver 50 adapted according to the present invention. A television receiver designed without knowledge of the novel use of the private data channel would simply discard data sequence information. Television receivers designed in accordance with the present invention, effectively utilize the data sequence information as described below to improve the quality of the received signal.

The digital television signal, including the packetized video, audio and private data sequences, is received and pre-processed by receiver front end 55 to demodulate the signal and to recover digital television stream 25. Recovered digital television stream 25*a* is essentially the same signal as digital television stream 25, but may have been degraded, corrupted, or otherwise affected by particular propagation characteristics of channel 600.

Private data stream 101 is recovered from digital television stream 25*a* by demultiplexer 60. As previously described herein, the information on the private data stream comprises a known data sequence. The received known data sequence is indicated in FIG. 1A as first data sequence 101. First data sequence 101 is provided to channel estimator 100. Also provided to channel estimator 100 is local data sequence 103. Local data sequence 103 is the same data sequence as first data sequence 101, except local data sequence 103 has not been affected by the characteristics of channel 600. Channel estimator 100 estimates the propagation characteristics of channel 600 by comparing local data sequence 103 to first data sequence 101. In other words, channel estimator 100 provides a channel estimate based on comparison of data sequence 102 and 103. In one embodiment of the present invention, the channel estimate comprises estimated channel impulse response signal 115 and estimated noise variance signal 120. Estimated channel impulse response signal 115 and estimated noise variance signal 120 are provided to coefficient processor 500.

Coefficient processor 500 determines filter coefficients, which, when applied to equalizer 300, causes equalizer 300 to undo the effects of channel 600 on recovered digital television stream 25*a*. Thus, multipath components and other distortions in the signal are filtered from the digital television signal. The filtered audio and video streams may then be recovered from the digital television signal and processed in accordance with methods and apparatus known in the art.

According to one embodiment of the present invention (not shown), a Least Mean Squares (LMS) algorithm is employed to obtain filter coefficients to be applied to equalizer 300. However, this technique has a drawback in that the convergence time of the least mean square (LMS) algorithm is inversely proportional to the smallest eigenvalue of the autocorrelation matrix of the received sequence (input to equalizer). On channels with severe multipath and in-band nulls, this smallest eigenvalue becomes very close to zero which could slow down the LMS equalizer convergence.

An embodiment of the invention that avoids this autocorrelation matrix problem is illustrated in FIG. 1A. The embodiment of FIG. 1A includes a channel estimator 100. Channel estimator 100 obtains a channel estimate and provides the channel estimate to coefficient processor 500. Coefficient processor 500 then uses the channel estimate to compute equalizer coefficients to be applied to the taps of adaptive equalizer 300. The term channel estimate, as used herein means the channel characteristics as represented by the impulse response signal 115 and estimated noise variance signal 120. Channel impulse response signal 115 is estimated based on comparison of data sequence 101 (embedded in each transmitted block of the digital television bit steam 25), and locally generated data sequence 103. The channel estimate is then used, together with an estimate of the channel signal-to-noise ratio (SNR), i.e., estimated noise variance signal 120, to compute the optimum coefficients of adaptive equalizer 300. Received digital television stream 25*a* is applied to the input of equalizer filter 300. The response of equalizer 300 to digital television stream 25*a*, as

determined by equalizer coefficients 130 and 140, is such that undesirable channel effects on digital television stream 25*a* are filtered from digital television stream 25*a*.

Channel Estimator

One embodiment of channel estimator 100 is depicted in FIG. 2. As previously described, a known data sequence 101 is transmitted over a channel 600. The received data sequence signal 101 has passed through channel 600 and has likely been corrupted by noise. Data sequence 101 is applied to first Fast Fourier Transformer (FFT) 102 which computes the FFT of noisy and distorted received data sequence signal 101. Locally generated data sequence 103 is generated by second data sequence generator 148 (best illustrated in FIG. 1A) and applied to second Fast Fourier Transformer 104. Second FFT 104 computes the FFT of second data sequence 103. Divider 105 divides the FFT of the received signal by the FFT of the locally-generated data sequence. The output of divider 105 is an estimate of the channel frequency response.

The channel impulse response signal 115 is computed by Inverse FFT (IFFT) 106 which computes the inverse FFT of the computed channel frequency response output from divider 105. The resulting time-domain response is provided to window circuit 107 to obtain an estimated channel response $\hat{h}=[h_0\ h_1\ \ldots\ h_v]$. The starting location and width of window 107 is determined by requiring that the windowed impulse response contains most of the energy (e.g., 99% or higher) of the un-windowed channel impulse response.

An estimate of the noise variance, and hence the channel signal-to-noise ratio (SNR) is determined by computing the average energy of the channel estimation error sequence. The channel estimation error sequence is equal to the difference output of subtractor 109. Subtractor 109 computes the difference between the actual received sequence and the estimated received sequence (formed by convolving in convolution function 108 the locally-generated training signal on channel 103 with the estimated windowed channel impulse response from the window function 107) and the received signal on channel 101. The average energy estimation is then computed by function 110 as

$$\frac{1}{L}\sum_{i=1}^{L}|o|^2,$$

where L represents the length of the received sequence, and |O| represents the absolute value of the received sequence function.

Once the channel impulse response and channel SNR estimates are available, they are provided to coefficient processor 500 and used to compute the optimum equalizer coefficients for equalizer 300.

Equalizer

The equalizer structure employed in one embodiment of the invention is the minimum mean square error decision-feedback equalizer (MMSE-DFE) shown in FIG. 3. This equalizer structure consists of two finite-impulse-response (FIR) filters 201, and 202. The first FIR filter is a feed forward filter 201 (denoted by w), and the second FIR filter is a feedback filter 202 (denoted by b). FIR filter 201 receives digital television stream 25*a* at an input and outputs a filtered signal to summer 204. The output of summer 204 is provided to a decision device 205. The output of decision device 205 is estimated symbols denoted $\hat{x}_{k-\Delta}$ This output is also fed back to FIR filter 202, the filtered output of which constitutes the second input to summer 204. It is this output that is subtracted from the output of FIR filter 201. The coefficient settings of the two FIR filters 201 and 202 are optimized to minimize the mean square value (or equivalently average energy) of the error sequence (which is equal to the difference between the input and output of the decision device 205 in FIG. 3). Previously detected-symbols, denoted in FIG. 3 by $\hat{x}_{k-\Delta}$, are fed back and filtered to remove their interfering effect of current and future symbols yet to be detected. The coefficients for both FIR filters 201 and 202 are provided by coefficient processor 500.

Coefficient Processor

In one embodiment of the present invention coefficient processor 500 computes the equalizer coefficients from impulse response signal 115 in a non-iterative (i.e., one shot) computation that has a closed form and is coded on a programmable digital signal processor (DSP) chip. In one embodiment of the present invention, computing the optimum equalizer coefficients from the channel impulse response estimate is accomplished by inverting a correlation matrix whose size is equal to the total (feed forward and feedback) number of equalizer taps according to methods well known to those of ordinary skill in the art of signal processing. Other equalizer computation algorithms suitable for use in conjunction with the present invention are known to those of ordinary skill in the art. In one embodiment of the present invention the equalizer computation algorithm is implemented on a commercially available programmable digital signal processor. In another embodiment of the present invention, the equalizer computations are implemented on an ASIC. As will be readily apparent to those of ordinary skill in the art, other integrated circuits or processor means may be employed to execute algorithms for computing equalizer coefficients.

A flow chart of the steps of a method and algorithm of the present invention implemented by coefficient processor 500 to compute the optimum filter coefficients of equalizer 300 is shown in FIG. 4. The estimated channel impulse response and estimated noise variance are used to construct the matrix R in function step 301, where

$$R = \frac{1}{SNR} I_{N+v} + H * H.$$

This matrix is then factorized in step 302 into the product of a lower-triangular matrix L,

$$L = \begin{bmatrix} 1 & 0 & 0 & 0 \\ x & 1 & 0 & 0 \\ x & x & 1 & 0 \\ x & x & x & 1 \end{bmatrix},$$

a diagonal matrix D,

$$D = \begin{bmatrix} d_1 & 0 & 0 & \cdots & 0 \\ 0 & d_2 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & d_{N+v} \end{bmatrix}, \text{and}$$

an upper-triangular matrix L*, where * denotes the complex conjugate transpose operation. This factorization is com-